

Theoretical and Experimental Study of Bubbly Gas-water Two Phase Flows through a Universal Venturi Tube (UVT)

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Abstract

Unlike single phase flows, the relationship between the phase flow rate and the pressure drop across a differential pressure device (e.g. Venturi) in multiphase flow measurements is not simple and should include the phase volume fractions or the mass flow quality. The research described in this paper studies the bubbly gas-water two phase flows through a universal Venturi tube. The bubbly flow is assumed to be homogenous in which the two phases are moved with the same velocity (i.e. the slip ratio is unity). A Universal Equation.3□□ □ (24) entage error, □EMBED Equation.in conjunction with the homogenous flow model, was combined with the flow density meter enabling the gas volume fraction and hence the mixture flow rate in bubbly gas-water two phase flows to be determined. It was inferred from the experimental results that the homogenous flow model starts to break when the gas volume fraction increases beyond 17.48%.

Keywords: Universal Venturi Tube, Two phase flow, Flow density meter, Bubbly flow

Introduction

In industrial fields the need to measure fluid flow rate arises frequently. The accuracy and repeatability of the flow rate measurements are necessary for process development and control. Differential pressure devices can be used in multiphase flow

metering. The most common differential pressure device is the Venturi meter, but orifice plates have also been used widely. The advantage of using the Venturi meter over the orifice plate is that the Venturi meter is much more predictable and repeatable than the orifice plate for wide ranging flow conditions. Furthermore, the smooth flow pattern in Venturi meter reduces frictional losses which increase the reliability of the Venturi.

The bubbly air-water two phase flow described in this paper was considered as a homogenous flow in which the velocity of the phases can be assumed equal (i.e. the slip ratio is unity). The universal Venturi tube used in this paper is shown in Figure 1. The dimensions of the Venturi meter are similar to the hydraulic shape described by [1].

Measurement of the gas volume fraction is important to determine the phase flow rate in multiphase flow applications. The differential pressure technique (i.e. flow density meter), in conjunction with the mathematical flow model, was used in this paper to measure the gas volume fraction. This technique is simple in operation, easy to handle, non-intrusive and low cost [2].

The gas volume fraction can be used in conjunction with the homogenous flow model to determine the predicted mixture (homogenous) volumetric flow rate. The predicted mixture flow rate can then be compared with the reference mixture volumetric flow rate to analyse the accuracy and the capability of the homogenous flow model. It was found that the homogenous flow model works well when the gas volume fraction approximately below 0.1748 (i.e. 17.48%). Beyond that the bubbly-slug transition occurred in which the assumption of equal phase's velocities is no longer valid.

Considerable theoretical and experimental studies have been published to describe mathematical models of Venturis in multiphase flow measurements. The study of multiphase flow through contraction devices is described for example by Murdock (1962) [3], Smith and Leang (1975) [4], Chisholm (1977) [5], Lin (1982) [6], de Leeuw (1994) [7] and Steven (2002) [8]. All of these correlations depend either on the mass flow quality, x or empirical constants. Online measurement of mass flow quality x is rather difficult and not practical in multiphase flow applications. Some of the correlations found in literature are summarised below [9].

- (i) Murdock studied the two phase flow through an orifice plate meter and his work was not restricted only to wet gas flows. Murdock developed a rational equation modifying the single phase equation by introducing an experimental constant (correction factor). Murdock's correlation considers two phase flow to be separated flow and he computed the total mass flow rate using an empirical constant (equal to 1.26) and by assuming that the quality of the mixture is known. The correction factor in Murdock's correlation was solely a function of the modified version of Lockhart-Martinelli parameter X_{mod} which is defined as the ratio of the superficial flows momentum pressure drops (and not the friction pressure drops as in the original definition by Lockhart-Martinelli parameter). The modified Lockhart-Martinelli parameter is given by;

$$X_{\text{mod}} = \sqrt{\frac{\Delta P_w}{\Delta P_g}} = \left(\frac{\dot{m}_w}{\dot{m}_g} \right) \left(\frac{k_g}{k_w} \right) \sqrt{\frac{\rho_g}{\rho_w}} = \left(\frac{1-x}{x} \right) \left(\frac{k_g}{k_w} \right) \sqrt{\frac{\rho_g}{\rho_w}} \quad (1)$$

where ΔP_w and ΔP_g are the differential pressures when the liquid and gas phases respectively flow alone, \dot{m}_w and \dot{m}_g are the water and gas flow rates respectively, k_g and k_w are the gas and water flow coefficients, ρ_g and ρ_w are the gas and water density respectively and x is the mass flow quality. The gas mass flow rate in two phase flow from Murdock's correlation can be written as;

$$\dot{m}_g = \frac{A_t k_g \sqrt{2 \Delta P_{TP} \rho_g}}{1 + 1.26 \frac{1-x}{x} \frac{k_g}{k_w} \sqrt{\frac{\rho_g}{\rho_w}}} = \frac{A_t k_g \sqrt{2 \Delta P_{TP} \rho_g}}{1 + 1.26 X_{\text{mod}}} \quad (2)$$

where ΔP_{TP} is the two phase pressure drop.

- (ii) Chisholm studied two phase separated flow through a sharp edge orifice plate. The Chisholm correlation is a function of the two phase pressure drop and the modified Lockhart-Martinelli parameter. The gas mass flow rate in the Chisholm correlation can be written as;

$$\dot{m}_g = \frac{k_g A_t \sqrt{2 \Delta P_{TP} \rho_g}}{\sqrt{1 + C X_{\text{mod}} + X_{\text{mod}}^2}} \quad (3)$$

where A_t is the total flow area during two phase flow and C is the 'Chisholm parameter' and is given (in terms of a slip ratio S) by;

$$C = \frac{1}{S} \sqrt{\frac{\rho_w}{\rho_g}} + S \sqrt{\frac{\rho_g}{\rho_w}} \quad (4)$$

- (iii) Lin developed his model on the basis of a separated flow model (for general stratified two phase flow) and compared his model against the experimental data. This comparison shows that the Lin model can be used to calculate the flow rate or the quality of gas-liquid mixture in the range 0.00455 to 0.328 of the density ratio ρ_g/ρ_w , and in the pipe size ranging from 8 to 75 mm. The Lin correction factor K is given by;

$$K = 1.48625 - 9.26541 \left(\frac{\rho_g}{\rho_w} \right) + 44.6954 \left(\frac{\rho_g}{\rho_w} \right)^2 - 60.6150 \left(\frac{\rho_g}{\rho_w} \right)^3 - 5.12966 \left(\frac{\rho_g}{\rho_w} \right)^4 - 26.5743 \left(\frac{\rho_g}{\rho_w} \right)^5 \quad (5)$$

The gas mass flow rate in Lin correlation can be written as;

$$\dot{m}_g = \frac{k_w A_t x \sqrt{2 \Delta P_{TP} \rho_w}}{K(1-x) + x \sqrt{\frac{\rho_w}{\rho_g}}} = \frac{k_w A_t \sqrt{2 \Delta P_{TP} \rho_g}}{K \left(\frac{\dot{m}_w}{\dot{m}_g} \right) \sqrt{\frac{\rho_g}{\rho_w} + 1}} \quad (6)$$

Mathematical Modeling of the Gas-water Two Phase Flow Through a Venturi Tube

Flow model of the Venturi meter

In the case of homogenous flow where the two phases are normally well mixed, the gas and water are assumed to have the same velocity. That is, the velocity ratio is unity ($S=1$). Figure 1 shows the air/water two phase flows in an inclined Venturi meter.

From figure 1(a), it is possible to write;

$$\Delta P_{ven} = P_1 - P_2 - \rho_w g h_t \cos \theta \quad (7)$$

where ΔP_{ven} is the pressure drop across the Venturi, ρ_w is the water density, h_t is the pressure tapping separation in Venturi, g is the acceleration of the gravity and θ is the angle of inclination from vertical (in this paper, the Venturi is oriented vertically, therefore $\theta = 0$, see Figure 1(b) for full dimensions).

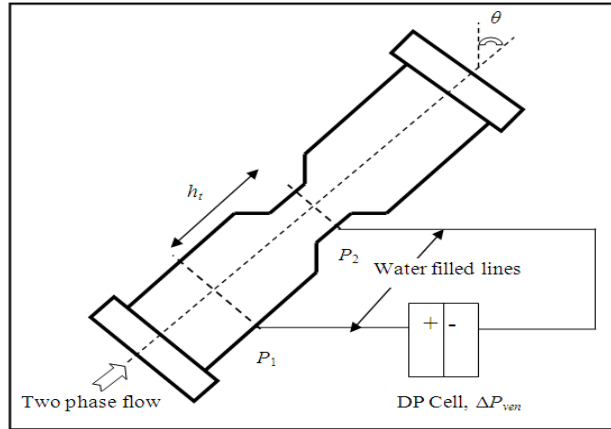


Figure 1 (a): Two phase flow through the Venturi


$$P_1 - P_2 = \frac{1}{2} \rho_m (U_2^2 - U_1^2) + \rho_m g h_t \cos \theta + F_{m,ven} \quad (8)$$
$$\rho_m = \alpha_g \rho_g + (1 - \alpha_g) \rho_w \approx (1 - \alpha_g) \rho_w \quad (9)$$
$$U_2 = U_1 \frac{A_1}{A_2} \quad (10)$$
$$U_2 = U_h \frac{A_1}{A_2} \quad (11)$$
$$\Delta P_{ven} = -\alpha_g \rho_w g h_t \cos \theta + F_{m,ven} + \frac{1}{2} \rho_w (1 - \alpha_g) U_h^2 \left\{ \left(\frac{A_1}{A_2} \right)^2 - 1 \right\} \quad (12)$$

It is well known that the mixture (homogenous) volumetric flow rate Q_m is given by;

$$Q_m = U_h A_1 \quad (13)$$

Substituting U_h from equation (12) into equation (13) gives;

$$Q_m = \frac{A_1}{\sqrt{\left(\frac{A_1}{A_2}\right)^2 - 1}} \sqrt{\frac{2}{\rho_w(1 - \alpha_g)}} \sqrt{\Delta P_{ven} + \alpha_g \rho_w g h_t \cos \theta - F_{m,ven}} \quad (14)$$

In terms of the discharge coefficient C_d , Eq (14) can be written as;

$$Q_m = \frac{C_d A_1}{\sqrt{\left(\frac{A_1}{A_2}\right)^2 - 1}} \sqrt{\frac{2}{\rho_w(1 - \alpha_g)}} \sqrt{\Delta P_{ven} + \alpha_g \rho_w g h_t \cos \theta} \quad (15)$$

It is clear from Eq (15) that the flow rate is a function of the pressure drop across the Venturi and the gas volume fraction. That is;

$$Q_m = f(\Delta P_{ven}, \alpha_g) \quad (16)$$

ΔP_{ven} in Eq (15) is measured directly from the dp cell (see figure 1(a)). The gas volume fraction α_g in Eq (15) can be measured using the flow density meter as described in section 2.2.

Measurement of the gas volume fraction using the flow density meter

The gas volume fraction α_g in Eq (15) can be measured by the differential pressure technique [10]. With reference to Figure 2 in which the tubes, connected to an upper and lower pressure tapping, are filled with water, it is possible to write;

$$\Delta P_{pipe} + F_{m,pipe} = g h_s \cos \theta (\rho_w - \rho_m) \quad (17)$$

where ΔP_{pipe} is the pressure drop across the vertical pipe, h_s is the pressure tapping separation ($h_s = 1\text{m}$) and $F_{m,pipe}$ is the frictional pressure loss term across parallel pipe.

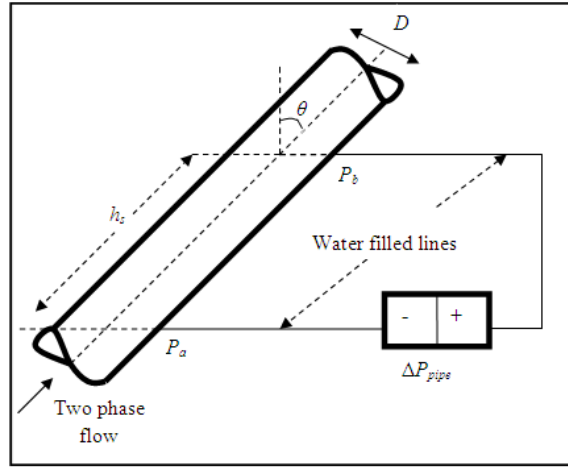


Figure 2: Measurement of the gas volume fraction

The frictional pressure loss term across parallel pipe is given by (Darcy's law);

$$F_{m,pipe} = \frac{2\rho_w h_s f U_h^2}{D} \quad (18)$$

where D is the inner pipe diameter and f is the single phase friction factor and is given by;

$$f = \frac{\Delta P_w D}{2\rho_w h_s u^2} \quad (19)$$

where u is the single phase (water) flow velocity and ΔP_w is the single phase (water) pressure drop across vertical pipe.

Substituting (9) into (17) and solving for α_g gives;

$$\alpha_g = \frac{\Delta P_{pipe} + F_{m,pipe}}{gh_s \cos\theta (\rho_w - \rho_g)} \quad (20)$$

Once the gas volume fraction α_g is measured, the mixture volumetric flow rate Q_m can be easily determined using Eq (15).

Experimental setup

The vertical bubbly gas-water two phase flow configuration, shown in Figure 3, is capable of providing flows with water as a continuous phase and air as a dispersed phase. This flow loop was used to study the universal Venturi tube using the homogenous flow model described in section 2. Combining the UVT with the flow

density meter (which was used to measure the gas volume fraction at the inlet of the UVT, see Figure 3) allows the mixture flow rate (see Eq (15)) to be determined.

As shown in Figure 3, the water was pumped to the test section which consists of the UVT and the flow density meter, through a turbine flow meter. The turbine flow meter was used to measure the reference water volumetric flow rate. The gas (air) was injected at the bottom of the test section through the thermal mass flow meter which was used to provide the reference gas flow rate. The air was passed through the regulator and the ball valve in which the reference gas flow rate can be manually controlled. The sum of the reference gas volumetric flow rate $Q_{g,r}$ (obtained from the thermal mass flow meter) and the reference water volumetric flow rate $Q_{w,r}$ (obtained from the turbine flow meter) gives the reference mixture volumetric flow rate, $Q_{m,r}$.

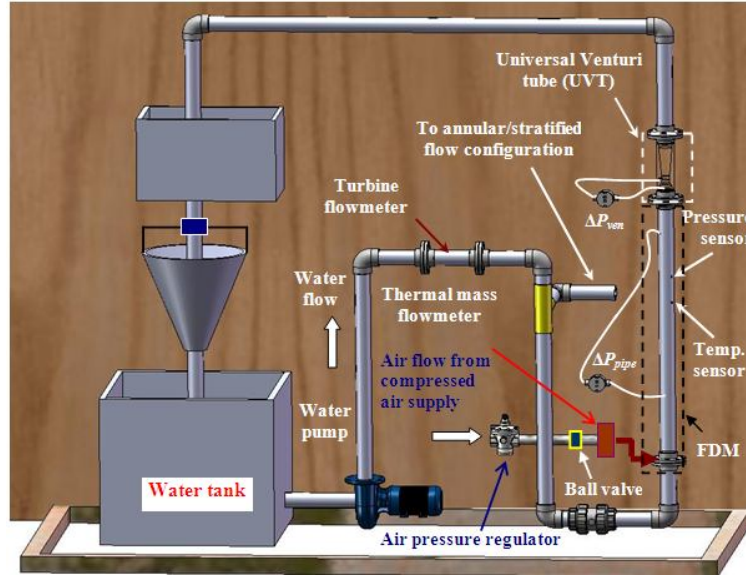


Figure 3: A schematic diagram of the vertical bubbly gas-water two phase flow configuration

The predicted mixture volumetric flow rate Q_n obtained from the homogenous flow model (see Eq (15)) can be compared with the reference mixture volumetric flow rate, $Q_{m,r}$ in which the percentage error in the Q_n can be analysed. Two DP cells were used to measure the differential pressure drop across vertical pipe and Venturi meter. A Yokogawa DP cell was used to measure ΔP_{pipe} across the vertical pipe (i.e. flow density meter) while a Honeywell DP cell was connected across upstream and the

throat of the UVT to measure ΔP_{ven} . Measurement of the pressure drops ΔP_{pipe} and ΔP_{ven} enables the gas volume fraction α_g (see Eq (20)) and the mixture (homogenous) volumetric flow rate (see (Eq (15))) to be determined respectively. Six signals were interfaced with a PC via Labjack-U12 (Figure 4); Two DP signals. (two I/V converters were needed to convert 4-20mA to 1-5V), gauge pressure signal, temperature signal, reference gas volumetric flow rate and reference water volumetric flow rate via CNT channel. (A sine to square wave converter was designed to convert the turbine flow meter sine wave output into a square wave). Once all required signals have been interfaced with LabJack-U12, the MATLAB test program was run and the required parameters were recorded (see Figure 4).

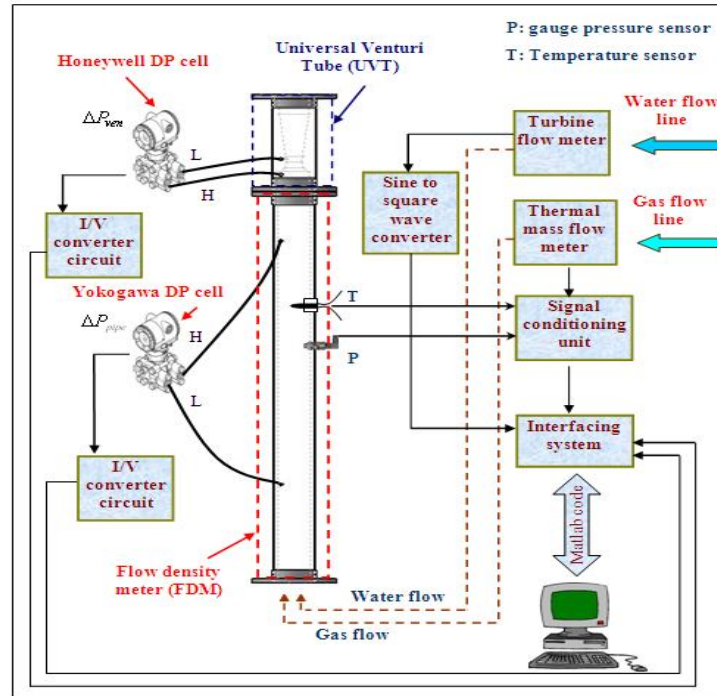


Figure 4: Measurement signals and interfacing system

Experimental Results and Discussion

Flow conditions of the bubbly (homogenous) gas water two phase flow through a UVT

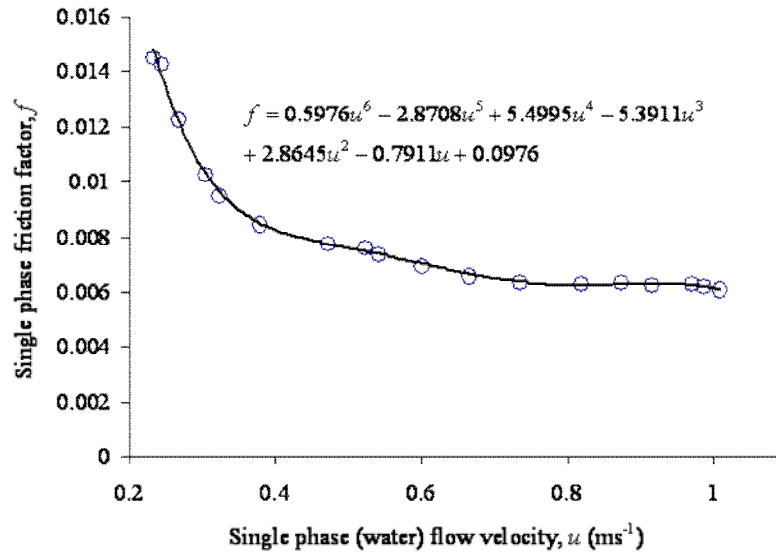
Experiments were carried out in vertical upward bubbly gas-water flows using a UVT. About 91 different flow conditions were tested and analysed. Three sets of data were tested as shown in Table-1.

Table-1: Flow Conditions

Flow conditions	Set-1	Set-2	Set-3
$Q_{w,r}$ (m^3s^{-1})	1.339×10^{-3}	1.937×10^{-3}	1.057×10^{-3} to 4.152×10^{-3}
$Q_{g,r}$ (m^3s^{-1})	3.329×10^{-5} to 1.264×10^{-3}	1.178×10^{-4} to 1.015×10^{-3}	2.648×10^{-5} to 1.181×10^{-3}

Flow loop friction factor calculation

Measurement of the pressure drop ΔP_w across a 1 m long pipe with different values of the water volumetric flow rate (and hence with different values of the water velocity, u) in conjunction with Eq (19) enables the single phase (water) friction factor f to be determined [11]. The experimental data in Figure 5 shows a classic increase in f as the flow velocity decreases. Eq (21) shows a good fit to the experimental data over the full range of flow velocities.

**Figure 5:** Friction factor variation with flow velocity

$$f = 0.5976u^6 - 2.8708u^5 + 5.4995u^4 - 5.3911u^3 + 2.8645u^2 - 0.7911u + 0.0976 \quad (21)$$

It should be noted that in order to determine the friction factor for bubbly (homogenous) flow, the superficial homogenous velocity U_h can be used in Eq (21). The superficial homogenous velocity is given by;

$$U_h = \frac{Q_{w,r} + Q_{g,r}}{A} \quad (22)$$

where $Q_{w,r}$ is the reference water volumetric flow rate measured directly from the turbine flow meter before water and gas were mixed (see Figure 3), $Q_{g,r}$ is the reference gas volumetric flow rate measured directly from the thermal mass flow meter and A is the cross sectional area of the pipe (see Figure 1(b)).

Replacing u in Eq (21) with U_h (see Eq (22)) enables the loop friction factor f to be determined in a bubbly gas-water flow. Once the friction factor f for bubbly (homogenous) flows is obtained, the frictional pressure loss term $F_{m,pipe}$ across parallel pipe in Eq (18) can be easily determined (and hence the gas volume fraction α_g in Eq (20) can be obtained). Note that, measurement of α_g enables the predicted mixture (homogenous) volumetric flow rate Q_m (see Eq (15)) to be determined.

Variation of the discharge coefficient

A discharge coefficient (see Eq (15)) is a parameter introduced to account for the frictional and turbulent losses in a Venturi meter [7]. In the literature, the value of the discharge coefficient for single phase (water) flow is always less than unity. The discharge coefficient C_d in Eq (15) can be defined as;

$$C_d = \frac{Q_{m,r}}{Q_m} \quad (23)$$

where $Q_{m,r}$ is the reference mixture (homogenous) volumetric flow rate and Q_m is the predicted (theoretical) mixture volumetric flow rate.

Figure 6 shows the variation of the discharge coefficient C_d with the gas volume fraction α_g . It is clear that the values of C_d becomes unpredictable when α_g exceeded 0.1748. In other words, for $\alpha_g \leq 17.48\%$, the values of C_d can be treated as independent of α_g and can be averaged as 0.948.

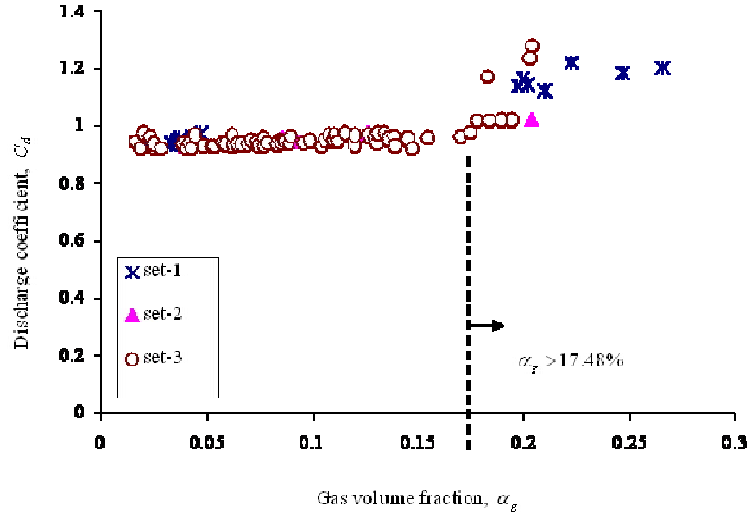


Figure 6: Variation of the discharge coefficient with the gas volume fraction

Variation of the pressure drop across the UVT in gas-water bubbly flows

Figure 7 shows the relationship between the pressure drop and the superficial homogenous velocity U_h . It is seen that when $\alpha_g \leq 17.48\%$, the trend can be approximated by a square root relationship which is very common relationship in single phase flow through a Venturi meter. For $\alpha_g > 17.48\%$, this approximation was no longer valid in which the points were moved away from approximated curve. This was due to the effects of the transition of a bubbly flow into a slug flow.

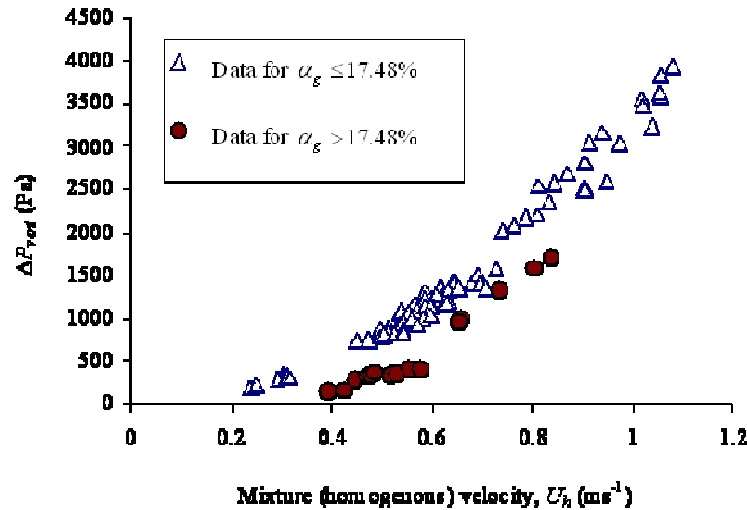


Figure 7: Variation of the pressure drop and superficial homogenous velocity through a UVT

Percentage error in the predicted homogenous volumetric flow rate through the UVT in gas-water bubbly flow

As can be seen from Figure 6, the discharge coefficient C_d in a bubbly gas-water flow was averaged as 0.948. To analyse the percentage error, ε , between the reference and the predicted mixture volumetric flow rates (Eq (15)) in bubbly (homogenous) gas-water two phase flows, two different values of C_d (0.94 and 0.95) other than the average value of the discharge coefficient were used to show the variation of the mean value error, $\bar{\varepsilon}$, at different values of C_d .

$$\varepsilon = \left\{ \frac{Q_m - Q_{m,r}}{Q_{m,r}} \right\} \times 100 \quad (24)$$

Figures 8 to 10 show the variation of the percentage error, ε in the predicted mixture volumetric flow rate Q_m with the gas volume fraction α_g at different values of C_d .

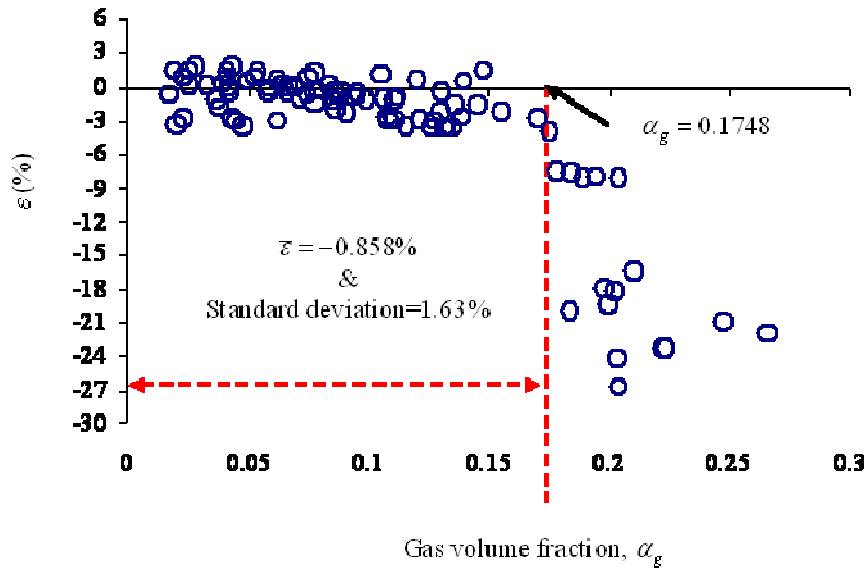


Figure 8: Percentage error in Q_m at $C_d = 0.94$

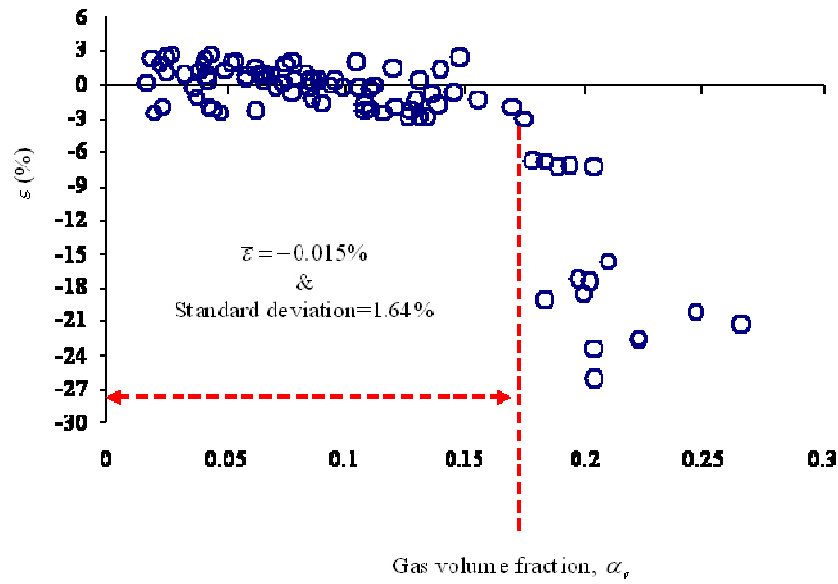


Figure 9: Percentage error in Q_m at $C_d = 0.948$

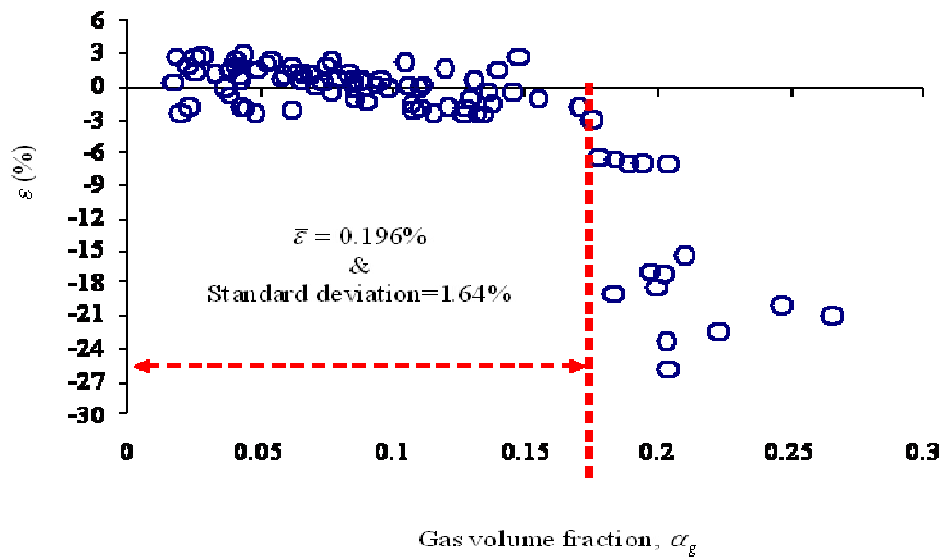


Figure 10: Percentage error in Q_m at $C_d = 0.95$

It is seen from Figures 8-10 that the homogenous flow model starts to break when the gas volume fraction α_g exceeds 17.48% in which the error was increased to about 30%. This was due to the transition between bubbly and slug flow regimes. The homogenous flow model is based on the unity slip ratio assumption (i.e. equal phase

velocities). However, for $\alpha_g > 17.48\%$, this assumption is no longer valid and the slip ratio effect should be introduced in the flow model.

Conclusion

The homogenous flow model was derived for the bubbly gas-water two phase flows through a universal Venturi tube. The gas volume fraction was measured using the differential pressure technique (i.e. flow density meter). The homogenous flow model in conjunction with the differential pressure technique was used to predict the mixture volumetric flow rate (Eq (15)) through the Venturi meter.

From the comparison between the predicted mixture volumetric flow rate Q_m (see Eq (15)) and the reference mixture volumetric flow rate $Q_{m,r}$ (obtained from the turbine flow meter and the thermal mass flow meter, see Figures 3 and 4), it can be concluded that the homogenous flow model starts to break when the gas volume fraction increased beyond 17.48%. This was due to the bubbly-slug transition flow. In this case the homogenous flow model should be modified to account for the slip ratio between the phases.

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